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Integrated and dynamic energy modelling of a regional system: A cost-optimized approach in the deep decarbonisation of the Province of Trento (Italy)

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A B S T R A C T

Since the Kyoto Protocol (1997), the European Union has fought against climate change adopting European, national and regional policies to decarbonise the economy. Moreover, the Paris Agreement (2015) calls 2050 solutions between -80% and -100% of greenhouse gas emissions compared with 1990. Regions have an important role in curbing CO2 emissions, and tailor-made strategies considering local energy demands, savings potentials and renewables must be elaborated factoring in the social and economic context. An "optimized smart energy system" approach is proposed, considering: (I) integration of electricity, thermal and transport sectors, (II) hourly variability of productions and demands, (III) coupling the EnergyPLAN software, to develop integrated and dynamic scenarios, with a multi-objective evolutionary algorithm, to identify solutions optimized both in terms of CO2 emissions and costs, including decision variables for all the three energy sectors simultaneously. The methodology is tested at the regional scale for the Province of Trento (Italy) analyzing a total of 30,000 scenarios. Compared to the Baseline 2016, it is identified: (I) the strategic role of sector coupling among large hydroelectric production and electrification of thermal and transport demands (heat pumps, electric mobility), (II) slight increases in total annual cost, +14% for a -90% of CO2 emissions in 2050.

1. Introduction

Since the signing of the Kyoto Protocol (1997) [1], the European Union (EU) and its Member States have committed themselves to a path aimed at fighting climate change through the adoption of EU, national and regional policies to decarbonise the economy. This path was confirmed during the 21st United Nations Climate Change Conference, COP 21, held in Paris in 2015, which by Decision 1/CP21 adopted the Paris Agreement [2]. The Paris Agreement establishes the need to contain the increase in global average temperature well below 2 °C and the pursuit of efforts to limit the increase to 1.5 °C, compared to pre-industrial levels.

Consistent with the Kyoto and Paris agreements, the EU has set its own targets for progressively reducing greenhouse gas emissions up to 2050. Currently, the main goals (from 1990 levels) are set out in the following documents: (I) 2020 climate and energy package (-20%) [3], (II) 2030 climate and energy framework (-40%) [4], (III) 2050 long-term strategy (between -80% and -100%) [5]. The EU recognizes this path as "deep decarbonisation" [6]. Each EU Member State is required to contribute to the achievement of the overall targets with its own specific national plans validated by the EU itself. Moreover, also each region has an important role to play as meeting the decarbonising goals calls for the elaboration of tailor-made plans that consider local energy demands and available renewable energy sources (RES) as well as the potential of energy

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efficiency improvements while factoring in the social and economic context. As an example, Cormio et al. [7] underlined the importance of adapting the energy modelling to the regional characteristics and requirements, with a case study in the Apulia region in the Southern Italy, Terrados et al. [8] proposed the SWOT (strengths, weaknesses, opportunities and threats) analysis as an effective means to identify current problems and to envisage future action lines to redesign a regional energy system and encourage renewable energy development and environmental preservation.

The transition process is monumental calling for appropriate tools to design appropriate pathways. To model deep decarbonisation scenarios, based on an increasing RES penetration in the overall energy system, it is required an integrated view of the electricity, thermal and transport sectors, considering the seasonal and daily RES availability with respect to demand profiles. Several papers have shown the benefits of sector coupling modelling compared to single sectors modelling. Among them, Brown et al. [9] studied the cross-sector and cross-border integration in a cost-optimized, highly renewable European energy system. Bramstoft et al. [10] showed the advantages of the integrated modelling of transportation, electricity, gas, fuel refinery, and heat systems for the decarbonisation pathways of Sweden at 2050. Lund et al. [11] underlined the importance of moving beyond the electricity-only approach and towards an integrated cross-sector approach. Moreover, several papers have also shown that the temporal resolution is particularly important in the modelling of energy scenarios with high penetration of variable renewable energy sources (VRES). Among them, Poncelet et al. [12] analyzed how the temporal resolution should be prioritized compared to the techno-economic resolution and how the use of a low number of time-slices (usually 12 time-slices) generates a non-negligible error.

Therefore, the challenge is to develop integrated and dynamic scenarios that answer the following questions: (I) “is it possible to achieve the decarbonisation targets identified at European, national and regional level?” (II) “using which technologies?” (III) “at what cost?“.

Several computer tools to support energy planning and energy scenarios are available. Connolly et al. [13] reviewed 37 different computer tools that can be used to analyse the integration of renewable energy; the results provide the information necessary to select an appropriate energy tool for analysing the integration of renewable energy into various energy systems under different objectives. More recently, Ringkjøb et al. [14] presented a thorough review of 75 modelling tools used for analysing energy and electricity systems; increased activity in energy modelling in recent years has led to several new models and modelling capabilities, particularly focused on the integration of variable renewables. Both top-down and bottom-up approaches have specific advantages and limitations, as described by Herbst et al. [15].

This paper is oriented towards the concept of “smart energy system” (SES), proposed by Lund [16], where the dynamic synergies among all the energy sectors are exploited to develop new forms of flexibility [17]. Indeed, only by coordinating and integrating productions, storages, distributions and demands, among electricity, thermal and transport sectors, the overall energy system is able to compensate for the lack of flexibility of RES [18]. The SES concept is integrated in the advanced computer model called EnergyPLAN [19], a deterministic input/output model based on a bottom-up approach, built to dynamically analyse environmental and economic performances of energy scenarios. On an hourly scale, the model simulates a balance between the demands for electricity, heating and transport and the overall productions. EnergyPLAN has been applied in more than 100 journal articles [20], and is thus a well-established tool.

Reducing CO2 emissions, decreasing dependency on foreign sources, integrating local RES, while also minimizing energy costs, is a complex challenge which requires a wide analysis of several energy scenarios. Therefore, as optimizing an energy system is a multi-objective optimization problem, an advanced optimization tool is required to identify optimized scenarios. To address the problem, Mahbub et al. [21] first conceived the innovative integration of EnergyPLAN with a multi-objective evolutionary algorithm (MOEA). While the use of EnergyPLAN is bound to the simulation of a single energy scenario at a time, the integration of a MOEA enables the analysis of multiple scenarios, in a cyclical process in which they are compared on the base of specific objectives (e.g. CO2 emission and total annual cost[2] minimization). At the end, the whole range of simulated scenarios can be provided to the policy makers, distinguishing non-dominated solutions, on the Pareto front, and dominated solutions, above the Pareto front. The choice of solutions on, or close to, the Pareto front allows to define optimized policies.

The methodology based on EnergyPLAN + MOEA, considering CO2 emission and total annual cost minimization as optimization objectives, has been tested by Mahbub et al. in a case study on a municipality scale, Aalborg Municipality (Denmark) [21], and in two case studies on a Valley Community scale, Giudicarie Esteriori (Italy) [22] and Val di Non (Italy) [23]. The Aalborg case study includes decision variables only for the electricity and thermal sectors, with a 2050 future time target, while the two Valley Community case studies include decision variables for all the three energy sectors (electricity, thermal and transport), the Giudicarie Esteriori time target is 2013 while the Val di Non provides an analysis of the energy transition (2020, 2030, 2050). Moreover, the same methodology has been applied by some other authors (see also Table 1). Prina et al. on a regional scale in the case studies of South Tyrol in Italy [24] and Niederösterreich in Austria [25], however not integrating decision variables for the transport sector and limiting the analysis to 2050. Still on a regional scale, Bellocchi et al. in the case study of Valle d’Aosta in Italy [26], however limiting the analysis to 2050, with decision variables only in the electricity and transport sectors. On a national scale, in Italy, Prina et al. ([27–29]), however not integrating decision variables for the transport sector in the first and third cases, for the thermal and the transport sectors in the second case, and limiting the analysis to 2050 in the first and third cases, and Bellocchi et al. [30], with decision variables for all the three energy sectors but considering a not specific medium and long-time perspective.

The case study of this paper is the Autonomous Province of Trento (in Italian “Provincia Autonoma di Trento – PAT”). A new Provincial Energy-Environmental Plan (in Italian “Piano Energetico-Ambientale Provinciale – PEAP”), for the post 2020 period, has to be designed by the PEAP working group [31],[3] on the base of optimal decarbonising solutions. Moderate “Low Carbon” (LC) and rapid “Low Carbon +” (LC+) scenarios, respectively aligned and superior to the European targets, have to be identified and compared with “Reference” scenarios (REF), the latter characterized by the same current technology mix projected on future energy demand.

The purpose of this paper is to test the EnergyPLAN + MOEA tool

[2] Total annual cost is calculated by summing three different yearly costs: energy carriers cost (for the purchase of energy carriers), operating cost (to ensure the operation and maintenance of technologies), investment cost (for the purchase of technologies). The investment cost include interest rate.

[3] As defined by a specific PAT council resolution, the PEAP working group includes the main local stakeholders at the level of policy makers and research: “Agenzia per le Risorse Idriche e l’Energia” (APRIE), “Università degli Studi di Trento” (UNITN), “Fondazione Bruno Kessler” (FBK), “Fondazione Edmund Mach” (FEM).

Table 1
Literature review on energy modelling based on EnergyPLAN + MOEA, comparison on territorial scale, future time steps and decision variables. HP = heat pump, CHP = combined heat & power, PV = photo-voltaic, LPG = liquefied petroleum gas, GSHP = ground source heat pump, ICEV = internal combustion engine vehicle, BEV = battery electric vehicle, DH = district heating, LDV = light duty vehicle, HDV = heavy duty vehicles, FCEV = fuel cell electric vehicle.

Reference	Territorial scale	Future time steps	Decision variables
Mahbub et al. [21]	Municipality	2050	HP, CHP, PP, onshore wind, offshore wind, PV
Mahbub et al. [22]	Valley Community	2013	wood boiler, oil boiler, LPG boiler, GSHP, wood CHP, PV, petrol ICEV, diesel ICEV, BEV
Mahbub et al. [23]	Valley Community	2020, 2030, 2050	wood boiler, oil boiler, gas boiler, GSHP, solar thermal, wood CHP, PV, ICEV, BEV
Prina et al. [24]	Regional	2050	building energy efficiency, large DH HP, small individual HP, solar thermal, DH thermal storage, PV, biogas PP, battery, electrolyser, fuel cell, hydrogen storage
Prina et al. [25]	Regional	2050	building energy efficiency, HP, solar thermal, PV, wind, battery, electrolyser
Bellocchi et al. [26]	Regional	2050	electricity storage, petrol LDV, diesel LDV, electric LDV, diesel HDV, hydrogen HDV
This work	Regional	2030, 2050	solar thermal, HP, boiler/Indiv oil, boiler/Indiv LPG, boiler/Indiv gas, boiler/Indiv biomass, CHP biogas, CHP/Indiv gas, hydroelectric, PV, battery, ICEV, BEV, FCEV
Prina et al. [27]	National	2050	building energy efficiency, HP, PV, wind, pumped hydro, battery
Prina et al. [28]	National	2020, 2025, 2030, 2035, 2040, 2045, 2050	PV, on-shore wind, battery
Prina et al. [29]	National	2050	building energy efficiency, PV, on-shore wind, battery, powerline connections
Bellocchi et al. [30]	National	a not specific medium and long-time perspective	building energy efficiency, HP, natural gas consumption, PV, onshore wind, offshore wind, diesel LDV, gasoline LDV, electric LDV

on a regional scale, integrating all the three energy sectors and studying the energy transition from the current baseline (2016) to two temporal steps of strategic political importance: 2030 and 2050. The novel contribution of this paper, compared to the previous case studies of Mahbub et al., it is the analysis of a regional scale. Moreover, hydrogen storage and battery storage are introduced as new decision variables, providing additional flexibility options for the energy system modelling. Instead, the previous case studies presented by Prina et al. and Bellocchi et al. do not include decision variables for all the three energy sectors simultaneously and/or limit the analysis to 2050 or to a not specific medium and long-time perspective. The aim of this paper is not just to solve one case study but to improve knowledge by giving scientific contribution to methodological knowledge and to a class of problems, using the case study only to test the hypothesis.

The remainder of the paper is organized as follows. In Section 2, the applied methodology is described. In Section 3, the results are presented and discussed. In Section 4, conclusive remarks are provided.

2. Methods

As described in the Introduction, the transition to deep-decarbonized energy systems implies a high use of variable and non-programmable RES (such as solar and hydro) as well as a high level of integration between the electricity, thermal and transport sectors (sector coupling). This is a great challenge for the energy system modelling.

Based on these requests for a SES, this paper adopt the EnergyPLAN software, developed and maintained by Aalborg University (Denmark) since 1999, and used by many researchers, consultants, and policymakers worldwide [19]. The main purpose of EnergyPLAN is to support energy planning by simulating the operation of a specific energy system, considering the interconnections among the different energy sectors. In particular, EnergyPLAN evaluates the operation of a pre-selected energy system configuration by hourly balancing energy demand and supply driven by a set of priorities. The computational time is very short and several energy systems configurations can be compared with respect to energy, economic and environmental indicators. The definition and comparison of multiple scenarios is the basis to evaluate potential technological alternatives to reach the desired targets, which are usually defined based on environmental goals (i.e. CO2 emissions). However, while EnergyPLAN allows a manual definition of a number of scenarios, the use of a dedicated algorithm allows the automation of this process, increasing the number of alternatives that can be effectively generated and compared to reach the desired targets.

To use EnergyPLAN, a summary list of required inputs includes: (1) Energy demand (annual + hourly profiles), (2) Energy production (annual + hourly profiles), (3) Production mix of the national electricity grid, (4) Efficiencies (energy production, energy distribution), (5) CAPEX (investment cost), (6) Interest rate (6% in this study), (7) OPEX (operating cost), (8) Lifetime, (9) Energy carriers cost (annual + hourly profiles only for the national electricity market), (10) CO2 emissions of energy carriers. EnergyPLAN includes several energy carriers and several technological solutions, this paper considers options that are currently well known and of interest for the PAT case study (Fig. 1). Moreover, the technical, economic and environmental evolution of the EnergyPLAN inputs is considered in three time steps: 2016, 2030 and 2050 (see Supplementary Materials A).

The energy transition from the current baseline (2016) to two temporal steps of strategic political importance (2030 and 2050) is analyzed with the following methodological steps:

1) EnergyPLAN analysis of the PAT Baseline 2016;
2) Analysis of CO2 policies, local trends of energy demand, technological perspectives, throughout the time period considered;
3) Application of the EnergyPLAN + MOEA framework, with CO2 emission and total annual cost minimization as objectives, to identify “optimized scenarios & optimized indications” on the Pareto front;
4) Socio-political analysis of the “optimized indications” and, in the EnergyPLAN framework, modification of the “optimized scenarios” with consideration of main technological perspectives

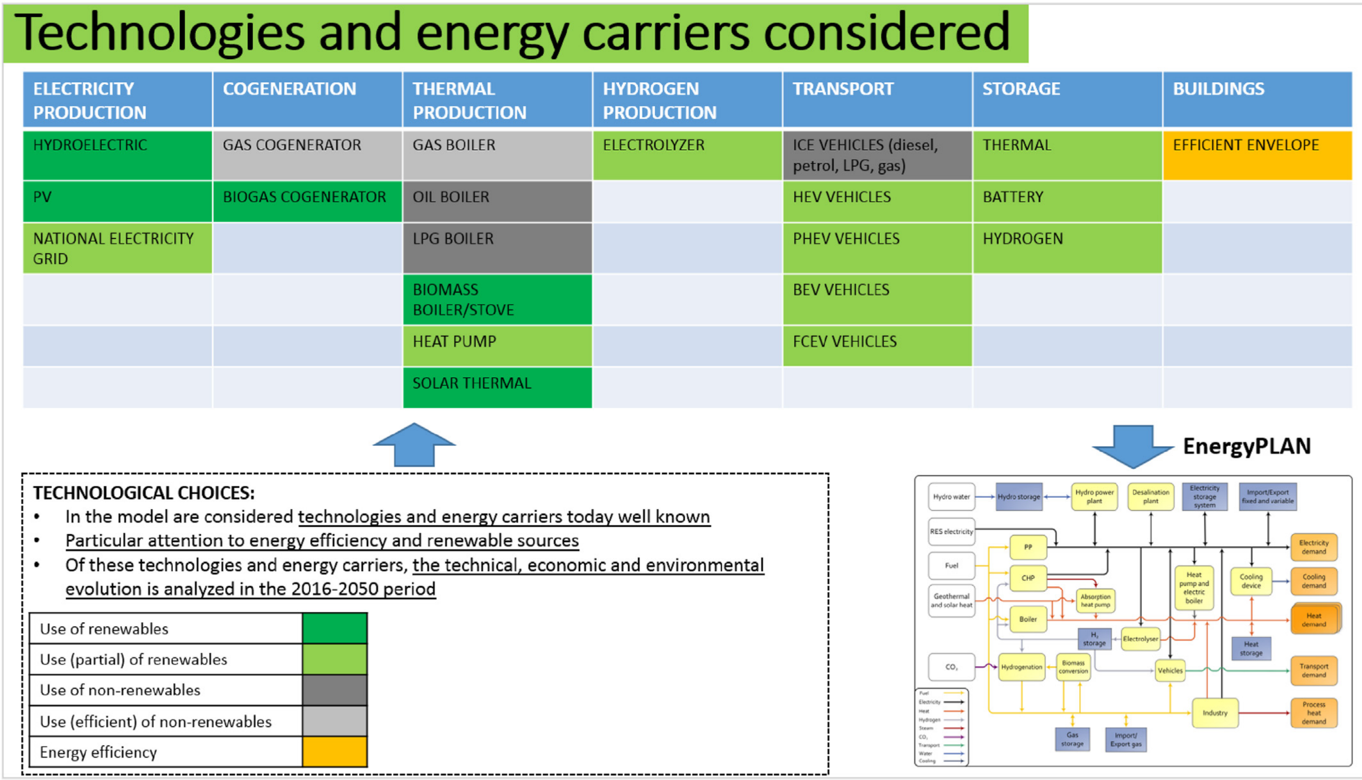

Fig. 1. Technologies and energy carriers considered in the PAT energy modelling.

and with an estimate of the impact of other factors (such as consumer choices and already existing regulatory constraints and incentive opportunities), to design realistic "Low Carbon scenarios" (LC, LC+) as close as possible to the Pareto front;

5) Comparison between the "Low Carbon" (LC, LC+) and the "Reference" (REF) trajectories, assessing environmental, economic and social benefits.

In the framework of CO2 policies, local energy demand trends and technological perspectives, the innovative combination of EnergyPLAN with MOEA gives an answer to an important question: "which scenarios allow to reach CO2 targets at the lowest cost?".

The identification of optimized energy scenarios can be formulated as a multi-objective optimization problem, due to the presence of more than one objective to be optimized (e.g. CO2 emission and total annual cost). Furthermore, the optimization of an energy system is a discontinuous problem in nature, therefore an advanced optimization tool is needed to manage this problem. In this regard, the framework developed by Mahbub et al. [21] is based on the integration of a MOEA and EnergyPLAN. While EnergyPLAN is able to simulate a single energy scenario at a time, the integration of a MOEA allows simulating multiple scenarios, in a cyclical process in which the scenarios produced are compared on the basis of the objectives identified. The framework is versatile enough to handle all the major sub-sectors of a SES.

The innovative integration of EnergyPLAN with MOEA is described in Fig. 2. The general steps of a MOEA are shown. Depending on the MOEA used, the implementation details regarding genetic operators (selection, crossover, mutation) and classification procedures (based on the concept of dominance) may be different. EnergyPLAN comes into play when, at each generation, individuals (energy scenarios) need to be evaluated. All required hourly distributions and costs are fixed EnergyPLAN inputs, since they do not change during the evolution of the algorithm. On the contrary, at each generation the MOEA produces new individuals in terms of new values of the decision variables (new capacities of the energy technologies), by using genetic operators. EnergyPLAN simulating the new individuals calculates all the output parameters. Among the outputs, the objective parameters (e.g. CO2 emissions and total annual cost of the scenario) are reported to the MOEA and used to rate the individuals. The cycle continues until a stop criterion is satisfied, which in our case is represented by a certain number of generations (enough to achieve convergence). After the completion of all generations, non-dominated individuals are presented as a Pareto front with optimized solutions. In this work the goal is to identify the Pareto fronts for the two time horizons of political interest, 2030 and 2050, by applying the EnergyPLAN + MOEA framework in two separate analysis. The Table 2 shows parameters used in this work.

Finally, to design realistic "Low Carbon scenarios" (LC, LC+), the EnergyPLAN + MOEA "optimized scenarios & optimized indications" on the Pareto front need to be combined with consideration of main technological perspectives and with an estimate of the impact of other socio-political factors (such as consumer choices and already existing regulatory constraints and incentive opportunities). Therefore, the proposed methodology allows a certain flexibility in defining the target technological mix, however, keeping the CO2 goals unchanged and total annual cost as close as possible to the Pareto front. The comparison between the Low Carbon (LC, LC+) and the Reference (REF) trajectories allows to assess environmental, economic and social benefits of energy decarbonisation.

3. Results

The Results section includes: (I) the case study description and

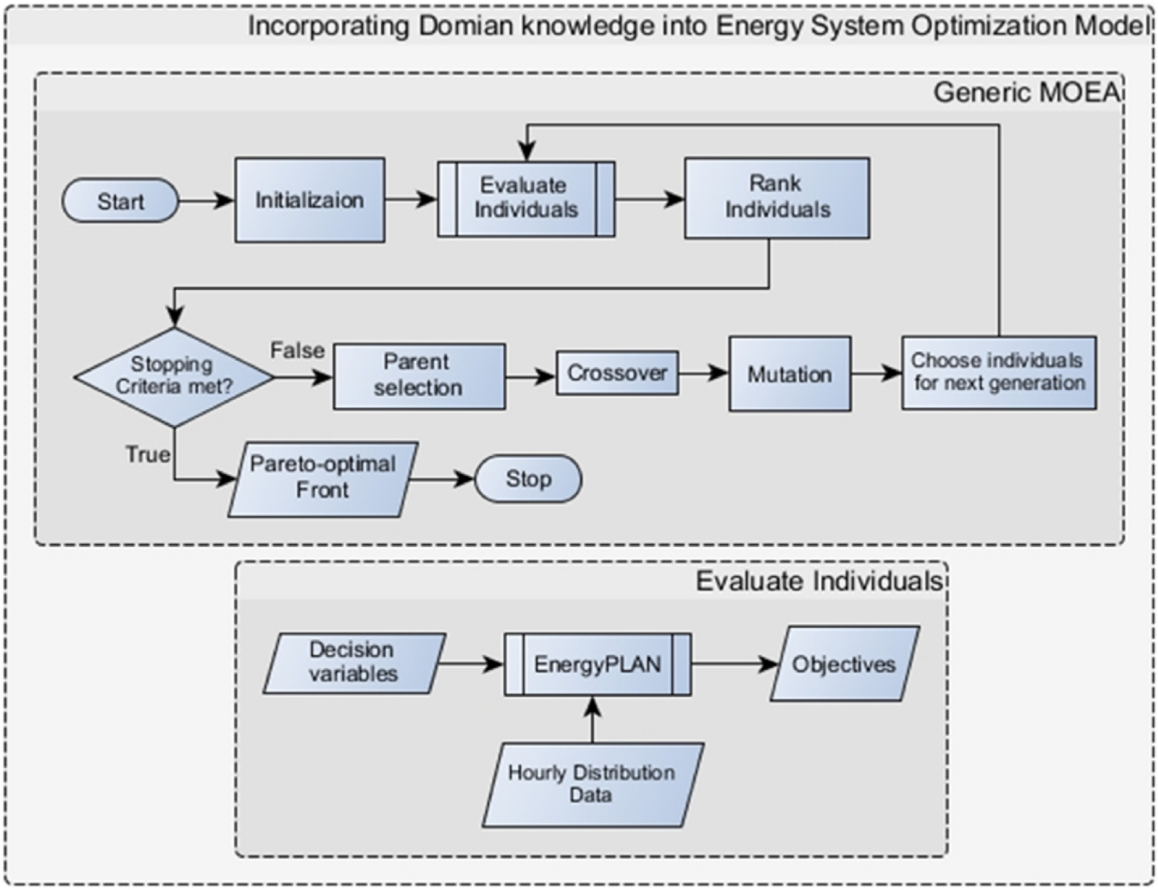

Fig. 2. Identification of “optimized smart energy systems”: the innovative approach combining EnergyPLAN + MOEA.

Table 2
Parameter values for EnergyPLAN + MOEA used in this work.

Parameters	Values[1]
Population Size	150
Generations	100
Crossover	SBX crossover
Crossover probability	0.9
Mutation	Polynomial mutation
Mutation probability	1/number of decision variables

[1] “The parameter settings of a meta-heuristics algorithms such as a MOEA is performed experimentally. All the parameters values in this experiment are set based on the authors’ experience of using the framework.”

the Baseline 2016, (II) the analysis of CO2 policies, local trends of energy demand and technological perspectives, (III) the analysis of future scenarios: optimized and PEAP scenarios.

3.1. *Case study description and Baseline 2016*

Trentino, officially the Autonomous Province of Trento (PAT), is an autonomous province of Italy, in the country’s northeast (Alpine Region). It is currently divided into 175 municipalities, with the government center in the city of Trento, covering an area of 6212 km^2, with a population of about 540,000 inhabitants. Analyzing the most recent data on annual energy flows [32], the Baseline PAT energy system in the year 2016 can be represented as in Fig. 3.

The overall energy use is 15,435 GWh, 47% for heat, 33% for transport, 20% for “pure electricity”.[4] The use of RES in the supply mix is equal to 34.8%, with the contribution of hydro 22.6%, biomass 9.4%, solar 1.7%, ambient heat 1.0% and the renewable part of the electric import (42.63% of the 0.1%). On the other hand, the use of non-RES is equal to the remaining 65.2%, with the contribution of gas 34.9%, oil 30.3% and the non-renewable part of the electric import (57.37% of the 0.1%).

In the electricity sector (Table 3), the annual production (5489 GWh) exceeds the annual consumption (3322 GWh) by 65%. Analyzing the hourly balances between production and consumption, 37.5% (2060 GWh) of the production is exported while 0.6% (20 GWh) of the consumption must be imported. These electricity exchanges are currently supported by the connection capacity. The local electricity production mix is very “green”, 78.7% from hydroelectric, 3.2% from photo-voltaic (PV) and 0.7% from biomass combined heat and power (biomass CHP). The non-renewable part is limited to the 17.3% from gas CHP. The large production from local RES enables an equivalent large consumption of RES, evaluated to be at 83%. In 2016, 94.0% of the electricity consumption is dedicated to the “pure demand”, 3.4% to the transport demand, 2.6% to the heat demand.

In the heating sector (heat demand 7240 GWh, Table 3), 97% of the demand is satisfied by individual heating while only 3% by district heating (DH). In 2016, 24% of the heating demand is satisfied by RES: biomass 18%, heat pump 4%, solar thermal 2%. The non-

[4] As agreed within the PEAP working group, the “pure” electricity demand includes all electrical demand excluding electrical demand for heat and transport counted in the corresponding sectors.

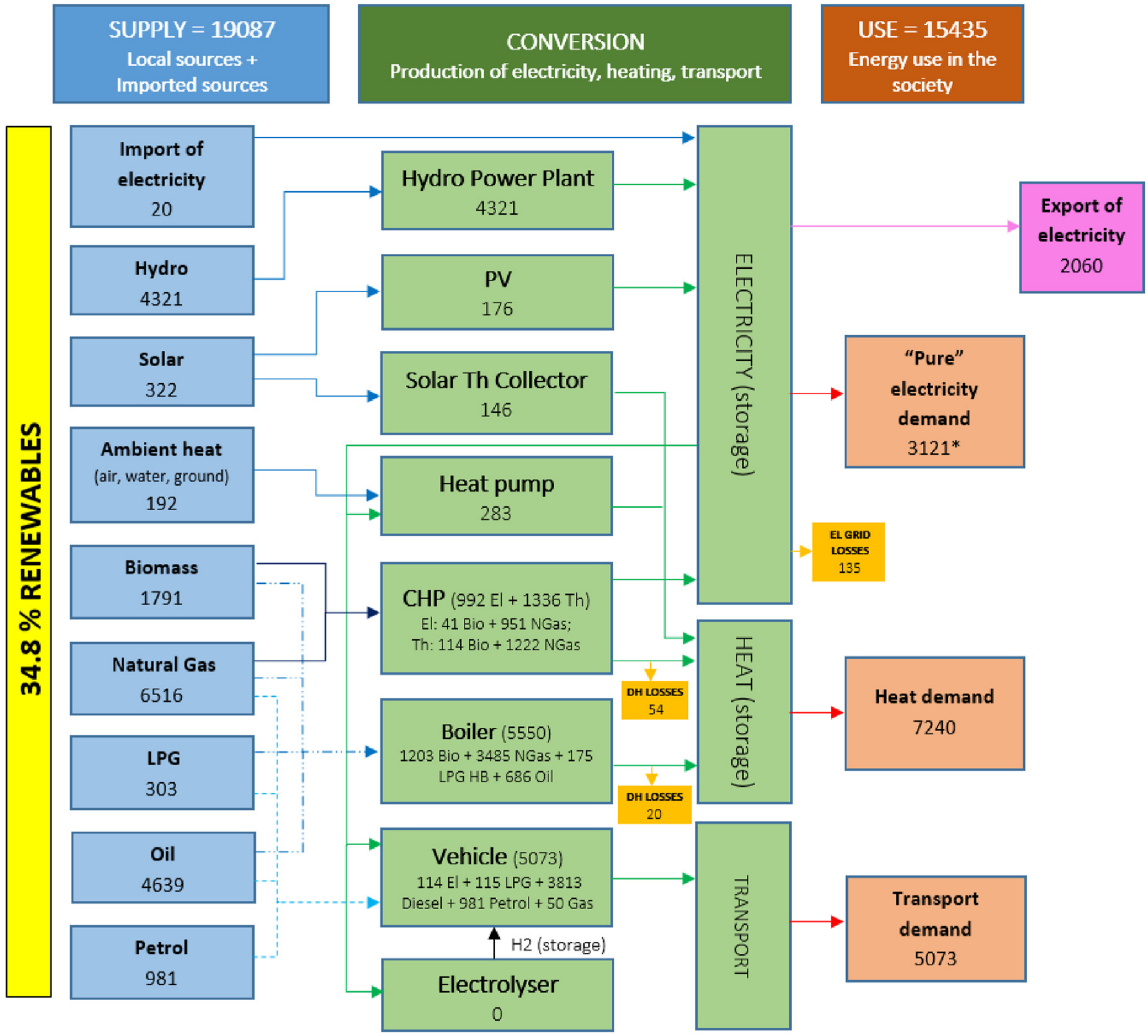

Fig. 3. Baseline PAT 2016: energy flow chart (GWh). * "Pure" electricity demand doesn't include electricity consumption for heat and transport counted in the corresponding sectors.

renewable part is dominated by gas with 64% followed by oil (10%) and liquefied petroleum gas (LPG, 2%). Most of the oil and LPG consumption is concentrated in some small valleys not yet reached by the gas network.

Finally, in the transport sector (transport demand 5073 GWh, Table 3), 75% of the demand is satisfied by diesel, 20% by petrol, 2% by LPG, 2% by electricity and 1% by gas. In 2016, only 2% of the transport demand is satisfied by RES, 98% by non-RES.

Integrating the annual data with several bibliographic references and PEAP working group considerations (Table 4), hourly profiling of productions, demands and national electricity market have been produced (see Supplementary Materials B).

The analysis of the 2016 PAT energy flows highlights and quantifies strengths and weaknesses of the local energy system. The PAT case study provides an exemplary model of how electrification could be considered a promising driver of renewables integration. Indeed, the case study is characterized by an abundance of renewable electricity production, mainly from hydroelectric power plants, which can be further exploited by increasing the electricity-based technologies in the heating (heat pumps replacing fossil fuel boilers [47]) and transport sectors (electric vehicles replacing fossil fuel vehicles [48]). This electrification approach is in line with multiple studies, from the global [49] to the national [50] and local scale [51].

3.2. *Analysis of CO2 policies, local trends of energy demand and technological perspectives*

The analysis of decarbonisation scenarios implies the definition of the CO2 goals to be achieved in specific time targets. On the one hand, PAT CO2 goals must comply with EU objectives, on the other hand, the autonomous government could envisage a faster decarbonisation trajectory, if technically and economically feasible and convenient. Based on these considerations, this study defines two types of decarbonisation scenarios:

- Low Carbon (LC):
  - o 2030: -40% CO2 emissions compared to 1990;
  - o 2050: -80% CO2 emissions compared to 1990.
- Low Carbon plus (LC+):
  - o 2030: -50% CO2 emissions compared to 1990;
  - o 2050: -90% CO2 emissions compared to 1990.

Table 3
Baseline PAT 2016: detailed sector balance.

	2016 (GWh)	Data source
ELECTRICITY SECTOR		
CONSUMPTION		
"Pure" electricity	3121	Terna [33]
"Heat" electricity	87	GSE [34], ENEA [35]
"Transport" electricity	114	Terna [33]
TOTAL	**3322**	
PRODUCTION		
Hydroelectric (normalized)	4321	GSE [34]
PV	176	Terna [33]
CHP biogas	19	Terna [33]/APRIE [36]
CHP/DH solid biomass	22	APRIE [36]
CHP/DH gas	105	AIRU [37]
CHP/industrial gas	846	Terna [33]
TOTAL	**5489**	
IMPORT/EXPORT		
Export	**2060**	*EnergyPLAN analysis*
Import	**20**	*EnergyPLAN analysis*
HEATING SECTOR		
Solar thermal	146	GSE [34]
Heat pump	283	GSE [34], ENEA [35]
CHP biogas	24	Terna [33]/APRIE [36]
CHP/DH solid biomass	68	APRIE [36]
CHP/DH gas	103	AIRU [37]
CHP/industrial gas	1087	Terna [33]
Boiler/DH solid biomass	23	APRIE [36]
Boiler/residential biomass	1132	AIEL [38]
Boiler/industrial biomass	41	GSE [34]
Boiler/DH gas	39	AIRU [37]
Boiler/residential gas	3079	MISE [39]
Boiler/industrial gas	355	MISE [39]
Boiler/residential LPG	175	MISE [39]
Boiler/DH oil	4	AIRU [37]
Boiler/residential oil	681	MISE [39]
TOTAL	**7240**	
TRANSPORT SECTOR		
Electric vehicles	114	Terna [33]
LPG vehicles	115	MISE [39]
Diesel vehicles	3813	MISE [39]
Petrol vehicles	981	MISE [39]
Gas vehicles	50	Servizio Commercio PAT [40]
TOTAL	**5073**	

Therefore, the LC scenarios are consistent with the EU energy and climate goals, the LC+ explore a "tech rapid" trajectory.

Once defined the CO2 goals, it is necessary to consider local energy demand trends and technological perspectives that, from the starting point of the Baseline 2016, lead to 2030 and 2050.

For the local energy demand trends, the following evaluation elements are considered:

- "Pure" electricity sector: population trend (ISTAT [52]), historical electricity consumption trend 2008–2017 (Terna [33]);
- Thermal sector: population trend (ISTAT [52]), building envelope efficiency trend 2014–2016 (ENEA [35]), the latter confirmed for the REF and enhanced for LC and LC+[5];
- Transport sector: population trend (ISTAT [52]).

The expected local energy demand trends are shown in Fig. 4. In the "pure" electricity sector, considering the average historical relationship, in the period 2008–2017, between the electricity consumption and population trends, an initial slight decrease in 2016–2020 is expected to be followed by an increase in the period 2020–2035 and then again a decrease in the period 2035–2050. In the thermal sector, the efficiency improvement of building envelopes determines a progressive decrease in heating demand, particularly in the LC and even more in the LC+ compared to the REF. In the transport sector, an increase in the population is expected to increase the vehicle stock and the number of kilometres (km) travelled; since "avoid" or "shift" phenomena are not considered in this study, the "decarbonisation" is focused on the concept of "improve" (increase in efficiency of traditional technologies, promotion of alternative vehicles).

For the technological perspectives, the following references are considered:

•REF:

o Scenarios that maintain the same technological mix as the Baseline 2016.

•LC, LC+:

o "Italian National Energy and Climate Plan (NECP)" (MISE 2018 [53]): for the hydroelectric, photo-voltaic (PV), solar thermal, heat pump modelling;
o "Report on tax deductions for the refurbishment of existing buildings" (ENEA 2018 [35]): for the implementation of energy efficient building envelopes;
o "Energy Storage Report" (POLIMI 2016 [54]): for the introduction of electric batteries as "energy reserve" coupled with PV;
o "Fuelling Italy's Future" (Transport & Environment 2018 [41]): for the transport sector modelling;
o FEM scenarios (FEM 2019): for the increase in biogas CHP production[6];
o PEAP working group considerations (APRIE, UNITN, FBK, FEM, 2018–2019) for the heating sector modelling:

- In the "Individual Heating" sector: (I) current political effort to prioritize the reduction of the oil and LPG boilers, due to low heat generation efficiency and high procurement costs, (II) current political effort to extend the gas network to some areas currently not supplied, due to high heat generation efficiency and low procurement costs, (III) users of biomass boilers are expected to remain constant at 2016 values, considering the limited social attractiveness to increase the use of biomass for energy purposes (wood procurement and policy issues related to the particulate matter emissions of wood combustion);
- In the "District Heating" sector: the 2016 DH characteristics are expected to remain constant, both in terms of number of users and type of technologies.

3.3. Analysis of future scenarios: optimized and PEAP scenarios

The analysis of future scenarios for the PAT case study is subdivided into a first part that describes the "optimized scenarios & optimized indications" and into a second part that describes the PEAP LC and LC+ scenarios. The LC and LC+ scenarios are compared with the REF scenarios to evaluate the difference between a trajectory that "freezes" the technological mix of the Baseline 2016 with two trajectories that evolve the technological mix to achieve (or exceed) the EU decarbonisation targets. Results are compared according to the following parameters: technologies for the heat

[5] In a REF scenario that maintains the same technological aptitude as the Baseline 2016, this trend (0.035 TWh/year of lower heating demand) is confirmed with a slight growth tied to the increase in population (up to a value of 0.037 TWh/year at 2030 and 0.039 TWh/year at 2050). In the LC and LC+ scenarios the REF values are revised upwards (by 20% in LC and by 50% in LC+).

[6] Compared to 2016, in 2030 +34/+50%, in 2050 +56/+85%, main sectors of increase: livestock, water purification.

Table 4
Data source and methodology for the PAT hourly profiles. TMY = typical meteorological year, SH = space heating, HSW = hot sanitary water, ICEV = internal combustion engine vehicles, HEV = hybrid electric vehicles, PHEV = plug-in hybrid electric vehicles, FCEV = fuel cell electric vehicles, BEV = battery electric vehicles, FIF = Fuelling Italy's Future [41], PUN = Prezzo Unico Nazionale, GME = Gestore dei Mercati Energetici.

	Data source and methodology
"Pure" electric consumption	HOURLY PROFILE: Terna - Transparency Report (hourly data Trentino-Alto Adige/Südtirol 2016) [33].
Hydroelectric Production	MONTHLY PROFILE: Hydro Dolomiti Energia (monthly data PAT 2007–2016) [42]. HOURLY PROFILE: Terna - Transparency Report (hourly data Trentino-Alto Adige/Südtirol 2010–2016) [33].
PV production	HOURLY PROFILE: PVGIS - TMY 2007–2016 [43].
Individual Heating	*SUBDIVISION OF CONSUMPTION: SH, HSW (23% of SH), cooking (10% of SH)* [36]: solar thermal, heat pumps, Boiler/residential biomass, Boiler/residential gas, Boiler/residential LPG, Boiler/residential oil; *industrial processes:* CHP biogas, CHP/industrial gas, Boiler/industrial biomass, Boiler/industrial gas. *HOURLY PROFILE: SH:* profile of the hourly heating degree days using the hourly temperature data from PVGIS - Trento TMY 2007–2016 [43]; *HSW:* UNI EN 15316-3-1:2007 [44]; *cooking:* FBK hypothesis; *industrial processes:* constant.
District Heating	*SUBDIVISION OF CONSUMPTION: SH, HSW (23% of SH), cooking (10% of SH)* [36]: CHP/DH solid biomass, CHP/DH gas, Boiler/DH solid biomass, Boiler/DH gas, Boiler/DH oil. *HOURLY PROFILE: SH:* profile of the hourly heating degree days using the hourly temperature data from PVGIS - Trento TMY 2007–2016 [43]; *HSW:* UNI EN 15316-3-1:2007 [44]; *cooking:* FBK hypothesis.
Solar thermal	HOURLY PROFILE: Hourly data of radiation and temperature from PVGIS - Trento TMY 2007–2016 [43]; use of the optical and thermal efficiency parameters of a standard flat solar panel.
Transport consumption	DAILY PROFILE: PAT 2016 traffic data (PAT Servizio Gestione Strade [45]). HOURLY PROFILE: 2016: FBK supply profile hypothesis for ICEV and electric trains; 2030 and 2050: FBK supply profile hypothesis for ICEV, HEV, PHEV (fuel), FCEV, electric train + FIF [41] charging profiles for PHEV (el) and BEV.
Electric market	HOURLY PROFILE: 2016: PUN 2016 (GME [46]); 2030 and 2050: average PUN 2013–2017 (GME [46]).

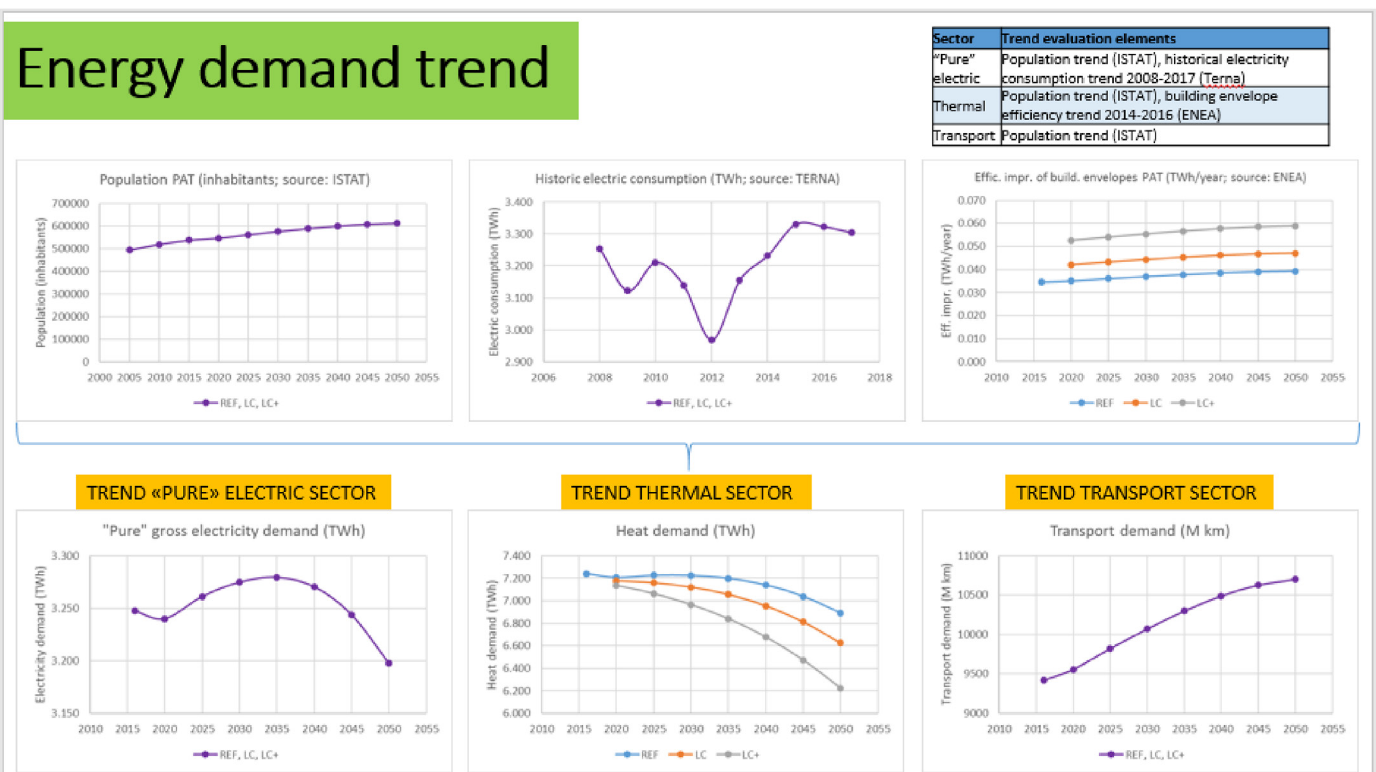

Fig. 4. Evaluation of local energy demand trends in the PAT case study.

demand, for the transport and for the electricity system, energy consumption, RES, CO2 emissions, costs.

In Fig. 5 the overall view, in terms of CO2 emission/total annual cost, of the scenarios elaborated for the year 2030 and for the year 2050, with decarbonisation performance compared to 1990 (in red dashed line). In order to compare CO2 emission and total annual cost performance between different years, these values are normalized with respect to the number of inhabitants. The grey scenarios are dominated solutions while the blue scenarios are non-dominated solutions, the latter representing the Pareto-front. Moreover, the Baseline 2016 is in yellow, the REF scenarios in orange, the LC scenarios in light green and the LC+ scenarios in dark green. It can be noted that in the methodological Step 4, the consideration of main technological perspectives and other socio-political factors did not resulted in an excessive distance of LC and LC+ from the Pareto front; by 2030 the LC/LC+ scenarios are 4/5% more expensive than the optimal solutions; by 2050 the gap is 8/7%.

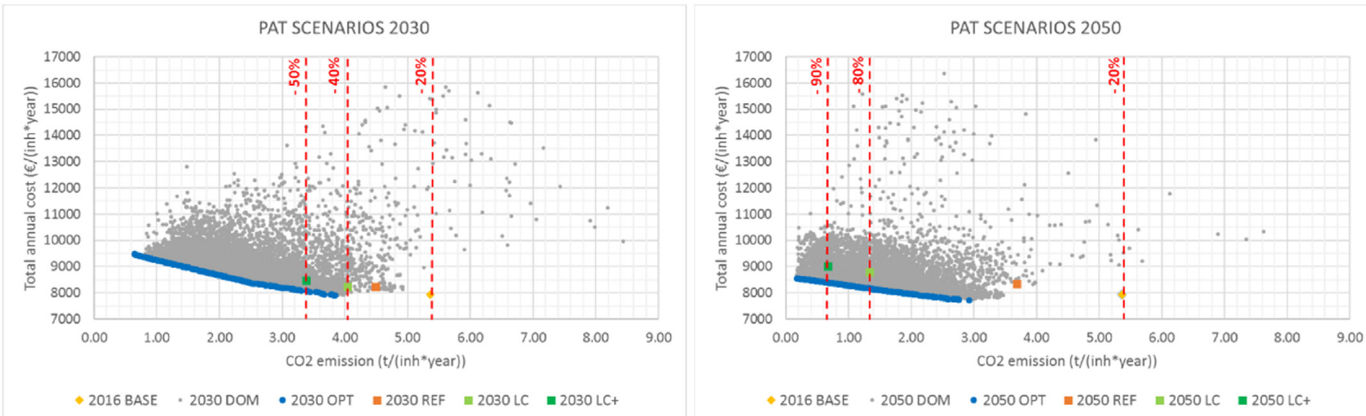

Fig. 5. PAT scenarios: results for 2030 and 2050. BASE = Baseline; DOM = EnergyPLAN + MOEA dominated; OPT = EnergyPLAN + MOEA optimized; REF = PEAP Reference; LC = PEAP Low Carbon; LC+ = PEAP Low Carbon +. Results of EnergyPLAN + MOEA consider the LC constraints. In red dashed line the reduction of CO2 emissions compared to 1990. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

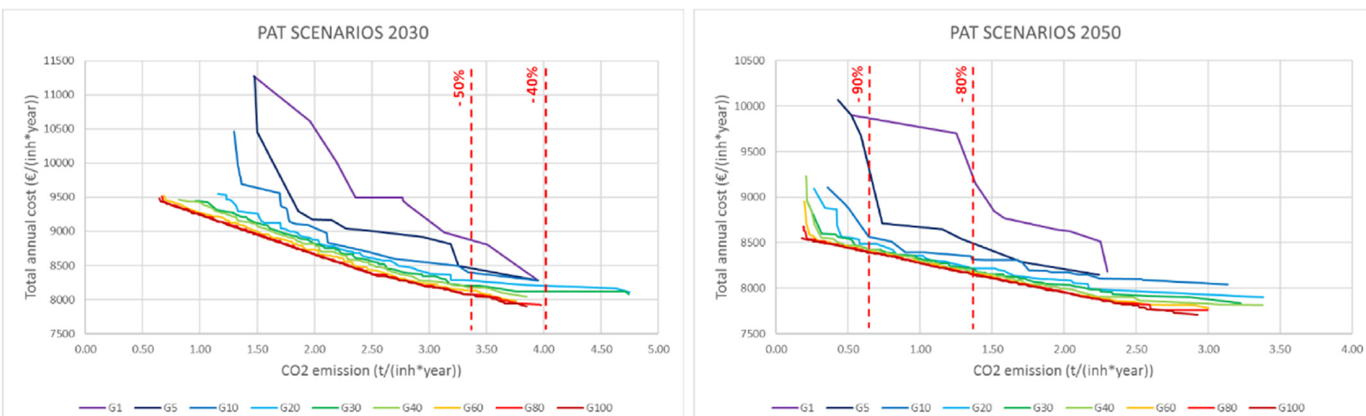

Fig. 6. PAT scenarios: progress of the Pareto front during the optimization, represented by the 100 generations performed by EnergyPLAN + MOEA to achieve convergence in 2030 and 2050. Results of EnergyPLAN + MOEA consider the LC constraints. In red dashed line the reduction of CO2 emissions compared to 1990. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. Optimized scenarios: results of the EnergyPLAN + MOEA framework

Combining 6 fixed value, 4 linked value and 14 variable value technologies, the latter within lower (LB) and upper (HB) boundaries, as defined in Fig. 14 of Appendix A, the EnergyPLAN + MOEA analysis has produced Pareto fronts with “optimized scenarios” for 2030 and 2050. For each time target, 100 generations have been performed to achieve convergence (Fig. 6) and 15,000 different combinations have been evaluated of which 150 represent the non-dominated solutions of the Pareto front.

Analysing the Pareto front solutions of Fig. 5, the technological results are illustrated and compared in Fig. 15 of Appendix B. The key messages of the EnergyPLAN + MOEA analysis, representing the “optimized indications”, are the following:

- PARETO FRONT SOLUTIONS: each point on the Pareto front represents a scenario that allows a CO2 target to be reached at the lowest possible cost through an optimal combination of technologies;
- CO2 EMISSION vs TOTAL ANNUAL COST: in 2030 Pareto front scenarios show a reduction in CO2 emissions between -43 and -90%, compared to the 1990 value, and total annual costs within +0/+20%, compared to the 2016 value; in 2050 reductions in CO2 emissions between -57 and -97% are combined with total annual costs variations within -3/+8%; technological progress will allow to reach increasingly ambitious CO2 targets at costs comparable to the current ones;
- INDIVIDUAL THERMAL SECTOR: maximum attractiveness for biomass boilers at all CO2 emission values, good for gas boilers and solar thermal only at high CO2 emission values, incremental for heat pumps moving towards low CO2 emission values[7];
- INDIVIDUAL COGENERATION: at all CO2 emission values, good attractiveness for biogas CHP (although in the reduced values of its potential), low for gas CHP;
- TRANSPORT SECTOR: good attractiveness for conventional vehicles (ICEV) only at high CO2 emission values, good for BEV only at low CO2 emission values, low for FCEV at all CO2 emission values;

[7] The solar thermal, in the PAT territory, is a renewable technology attractive to integrate up to about 20% of the total individual thermal demand, mainly in the summer season when the solar radiation reaches its maximum values. However, the achievement of very low values in CO2 emissions (i.e. less than -80% compared to 1990) determines the choice of technologies capable of providing attractive renewable thermal energy all year round, in these conditions solar thermal becomes a losing technology compared to heat pump.

- ELECTRIFICATION AND SECTOR COUPLING: at low CO2 emission values the electricity become the most attractive energy carrier, exploiting "green" production not only for "traditional pure electricity demands" but also in the thermal (heat pumps) and transport (BEV) sectors;
- DECARBONISATION OF INDIVIDUAL THERMAL SECTOR vs TRANSPORT SECTOR: to achieve the 2030 decarbonisation goals (between -40 and -50% of CO2 emission), interventions in the thermal sector are more attractive than those in the transport sector;
- ELECTRICITY PRODUCTION: at all CO2 emission values, maximum attractiveness for hydroelectric production, low for PV[8];
- ELECTRIC STORAGE: the use of electrical storage (batteries) is attractive in many scenarios both in 2030 and 2050;
- ELECTRICITY IMPORT/EXPORT: in 2050, the greater availability of hydroelectric power and the greater efficiency of heat pumps and BEV minimize the demand for electric import to achieve high CO2 reductions;
- LOCAL RES: at all CO2 emission values maximum attractiveness for the wide use of local hydro and local biomass, to which is added at low CO2 emission values the wide use of local ambient heat; the attractiveness of local solar is limited to the thermal use and up to values of 20% of the total individual thermal demand.

As previously described, the "optimized scenarios & optimized indications" from the EnergyPLAN + MOEA analysis need to be combined, in the EnergyPLAN framework, with consideration of main technological perspectives and with an estimate of the impact of other socio-political factors (such as consumer choices and already existing regulatory constraints and incentive opportunities) to obtain the realistic LC and LC+ scenarios proposed for the PEAP. For example, although PV does not represent an attractive technology for the PAT energy system, a considerable growth is expected, driven by already existing regulatory constraints [55] and already existing incentive opportunities [56,57]. The same for the industrial gas CHP, a slight growth is expected by 2030 linked to already existing incentive opportunities [56,57], instead, by 2050 the coherence with the EU decarbonisation targets impose a decrease. In the transport sector, the introduction of BEV is expected as early as 2030, indeed, although BEV are not attractive at this stage, a strong support will be provided by already existing incentives [56,57]. Another example is related to FCEV, for the benefit of a promising market to the already existing incentives [56,57] also some properties relevant to consumer choice are considered, such as longer autonomy and faster refuelling times compared to BEV [41]. The FIF study [41] confirms the FCEV attractiveness, highlighting the consumer choice factor and estimating a total cost of ownership (TCO) close to that of BEV, from +25% in 2030 to +15% in 2050.

3.5. PEAP scenarios: technologies for the heat demand

Starting from the heat demand technologies, PEAP results are shown in Fig. 7 and in Supplementary Materials C.

First of all, heating demand decreases thanks to the improvement of building envelope efficiency, in 2030 -2/-4% in LC/LC+ and in 2050 -9/-14% in LC/LC+. In the individual heating, the spread of heat pumps represents the main technological change in the decarbonisation path, moving from 4% in Baseline 2016 to 11/27% in LC/LC+ 2030 and to 43/64% in LC/LC+ 2050. In addition, solar thermal and biogas CHP increase, but slightly, while biomass boilers are kept stable. Among the fossil fuels, the use of gas represents a bridge between an energy system dominated by fossil fuels (2016) and an energy system dominated by RES (2050): (I) the outlook for the industrial gas CHP shows a slight growth by 2030 and then a decrease to 2050, (II) the outlook for the gas boilers shows a stability in LC 2030 while a decrease in LC 2050, LC+ 2030 and LC+ 2050 is expected. The use of oil and LPG boilers it is seen as a loser, from an environmental, efficiency and economy point of view, with a sharp fall by 2030, to then be absent in 2050. Finally, by choice of the PEAP working group, the district heating sector is unchanged, maintaining a stable 3% of the total PAT heat requirement.

3.6. PEAP scenarios: technologies for the transport

PEAP results of the transport sector are shown in Fig. 8 and in Supplementary Materials C. For a more detailed analysis than that of the EnergyPLAN + MOEA, the hybrid technologies HEV and PHEV are also considered.

First of all, despite the growth of the vehicle stock and of the number of km travelled, energy demand for transport significantly decreases with the transition to electric and hydrogen mobility (but also thanks to increasingly efficient ICEV), in 2030 -21/-27% in LC/LC+ and in 2050 -65/-67% in LC/LC+. Concerning electric mobility, the expected growth is from the 2% of transport energy consumption in Baseline 2016 to 6/9% in LC/LC+ 2030 and to 42/48% in LC/LC+ 2050. Hydrogen mobility, absent in Baseline 2016, is expected on an experimental basis in small captive fleets at 0.4/0.6% in LC/LC+ 2030, to then find a large market and reach an important share at 21/27% in LC/LC+ 2050.

3.7. PEAP scenarios: technologies for the electric system

The expected strong growth of heat pumps, electric vehicles and hydrogen vehicles increases the importance of the electricity sector. Therefore, PEAP results illustrated in Fig. 9 and in Supplementary Materials C should be analyzed with particular attention.

First of all, the increase in the gross electricity consumption driven by heat pumps and electric/hydrogen mobility is evaluated to be +9/+21% in LC/LC+ 2030 and +50/+64% in LC/LC+ 2050. During the same period, the growth of electric production is much lower, in 2030 +9% in LC/LC+ and in 2050 +15/+13% in LC/LC+. However, in all LC and LC+ scenarios, annual production remains higher than annual consumption. The most significant growth is for the PV while hydroelectric and biogas CHP show a smaller increase related to the limited additional availability of these RES. Moreover, the DH CHP is stable by choice of the PEAP working group while the industrial gas CHP goes up slightly by 2030 and then decreased to 2050. In optimizing the self-consumption of local resources, an interesting perspective is foreseen for the electricity storage, as an "energy reserve" coupled to PV thanks to an expected decrease in costs and to incentives (in 2030 a capacity of 46/79 MWh in LC/LC+, in 2050 a capacity of 290/483 MWh in LC/LC+). Finally, while the balance between import and export sees small variations in 2030, the 2050 massive electrification of the thermal and transport sectors involves an export decreasing and an import increasing.

Considering the importance of the electricity sector, a power analysis is performed. The EnergyPLAN output data allows an analysis of the hourly profiles in the electricity grid and of the maximum hourly power performed by consumption, production,

[8] The PV, in the PAT territory, is a renewable technology dominated by the local hydroelectric and by the RES of the imported electricity, which can guarantee cheaper renewable energy. Moreover, exceeding the local electrical demand, the local hydroelectric production is maximum in the summer period, between May and August, when the PV would show the greatest yield.

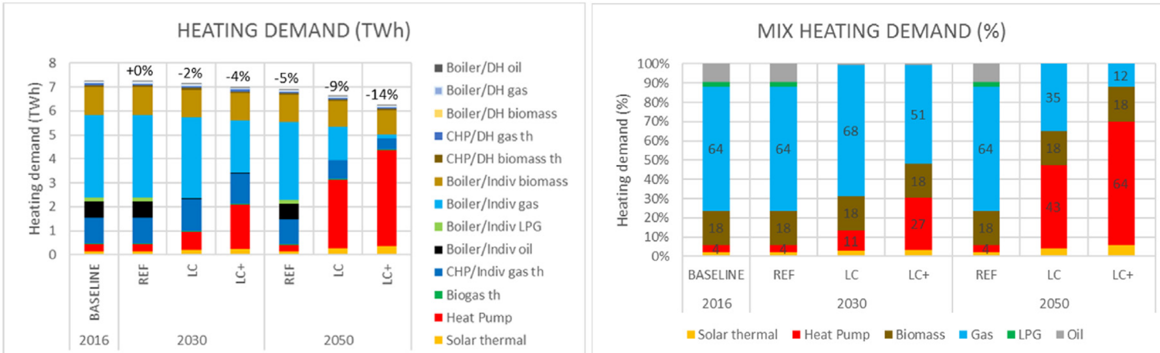

Fig. 7. PEAP scenarios - heating demand (graphic display).

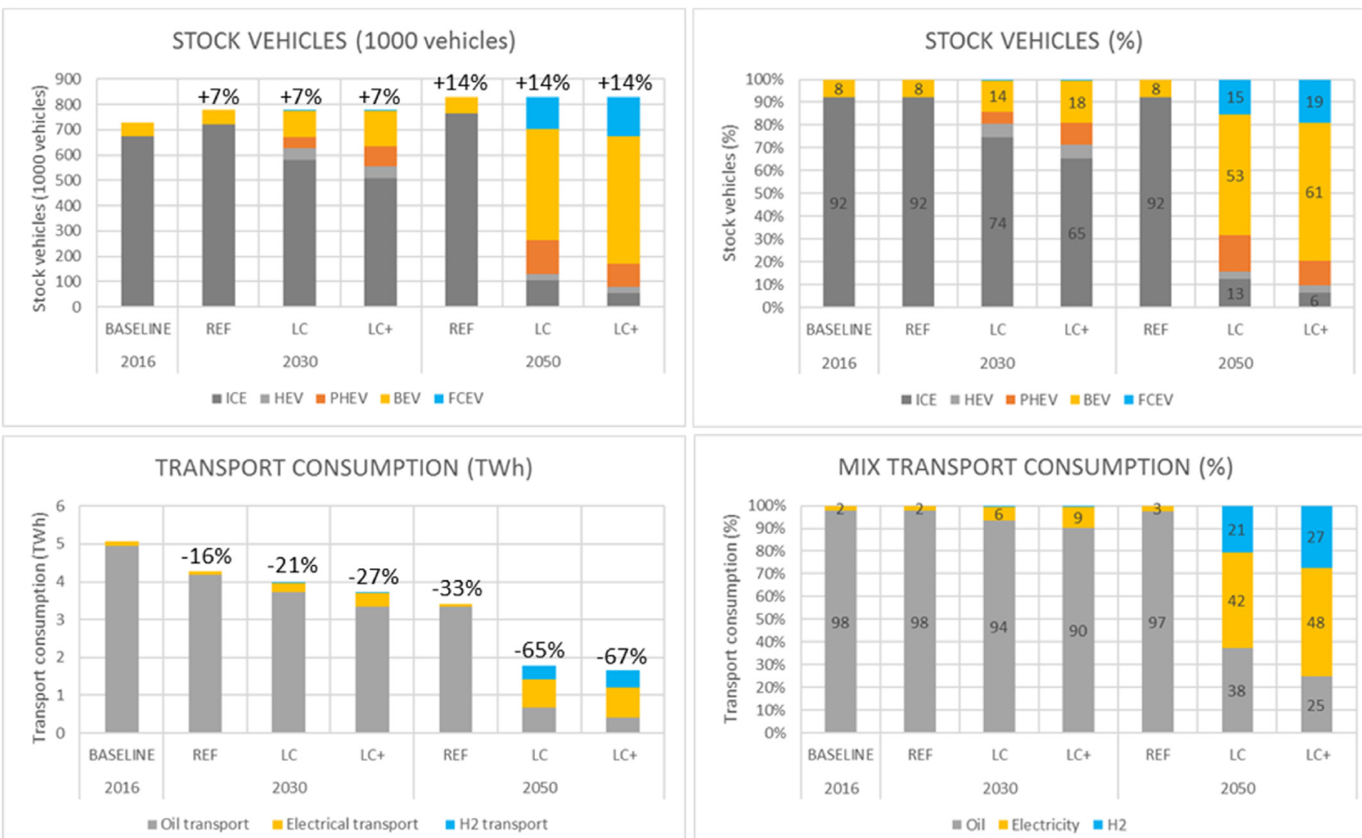

Fig. 8. PEAP scenarios - transport sector (graphic display).

import and export. It is also important to evaluate the growing operation of electricity storage, a key technology to enhance the balance between local production and local consumption. Results are shown in Fig. 16 of Appendix C, Fig. 10 and Supplementary Materials C.

In Fig. 16 of Appendix C interesting considerations emerge comparing the hourly profiles of electricity demand and electricity production, of the Baseline 2016 with those of the LC in 2030 and 2050, in the winter and in the summer period. Electricity demand shows an important increase in hourly power related to the electrification of thermal demand (heat pumps) and of transport (PHEV, BEV, FCEV). The increase is more marked in the winter period (higher thermal demand) and in the peaks of thermal demand (HSW, bands 7–8 and 20–21) and charging of electric vehicles (bands 7–11 and 17–21). The maximum increases in power are expected in the bands already critical for “pure” electricity demand (7–11 and 17–20). Electricity production shows a more limited increase in hourly powers. In fact, if on the one hand the PV and hydroelectric productions increase, on the other the CHP production decreases. The increase is more marked in the summer period, corresponding to the greater PV and hydroelectric production, especially in the middle of the day for PV and in bands 7–11 and 17–20 for hydroelectric. In the differential between production and consumption there are conditions of marked need for import in the winter, especially in the morning around 6–7 and in the evening around 21, and for export in the summer, especially around 11.

In Fig. 10 and Supplementary Materials C, interesting

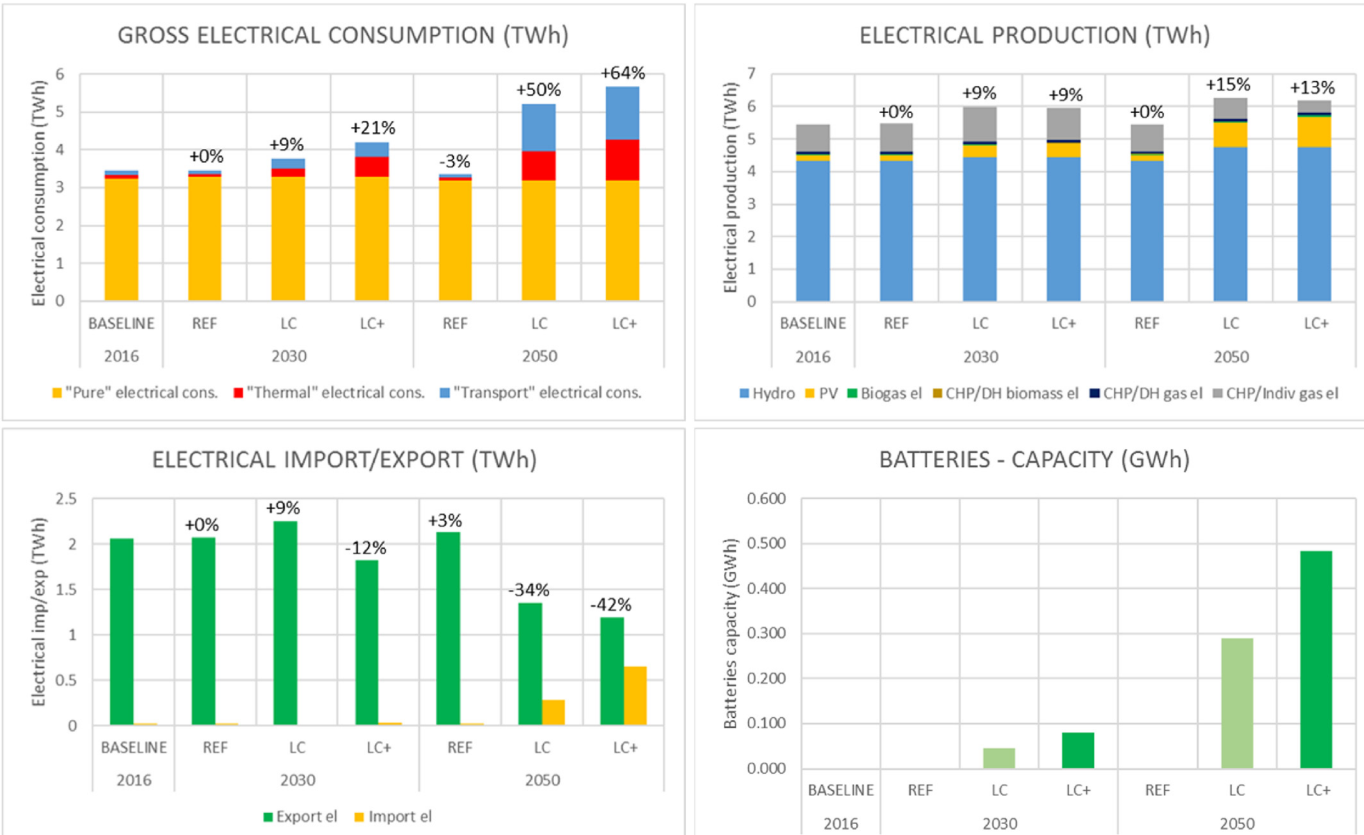

Fig. 9. PEAP scenarios - electricity sector (graphic display).

considerations emerge comparing the maximum hourly powers (MW) of the Baseline 2016 with those of the LC 2030 and LC 2050 scenarios. In the gross electricity consumption, a strong increase in power required for charging electric vehicles (25-71-256), heat pumps (35-90-313) and electrolysis (0-5-102) is foreseen. During the same period a strong increase is also expected for the PV (102-202-432) and the electric storage (0-23-145). In the local hourly balance between production powers and consumption powers an increase in both the powers required for export (860-931-954) and for import (179-184-332) is envisaged. Considering import and export, the exchange power with the national grid will have to increase by 11% between 2016 and 2050. This represents an important result of this study, suggesting a low impact of the electrification scenarios on the electrical exchange capacity with the national grid.

However, these data represent only a first indication of the impact on the electricity grid of the strong electrification envisaged in the PAT energy system. More detailed analysis, that can also assess the quality parameters (e.g. voltage and frequency), are recommended, particularly in highly urbanized areas.

3.8. PEAP scenarios: analysis of energy consumption, renewable energies and CO2 emissions

Looking at the PEAP scenarios as a whole, the use of more and more efficient technologies determines a progressive reduction of primary energy consumption. Compared to the Baseline 2016, in the LC/LC+ scenarios there is a drop of -16/-19% in 2030 and -37/-40% in 2050 (Fig. 11 and Supplementary Materials C).

Moreover, in the PAT energy supply mix there is a strong increase in the use of RES, which replace fossil fuels (Fig. 11 and Supplementary Materials C). Among the fossil fuels, in the transition phase of 2030, the use of gas remains stable in LC and slightly down in LC+ (-22%) while, in the following period 2030–2050, undergoes a sharp decline. At 2050 the gas consumption is expected to fall by -53% in LC and -80% in LC+, replaced in the heating sector by the ambient heat and also gradually reduced in its use for industrial CHP. Petroleum products (oil for heating, diesel and petrol for mobility) are expected to fall sharply as early as 2030 (-35/-41% in LC/LC+), even more to 2050 (-88/-93% in LC/LC+). The reasons for this sharp decline are the total loss of the heating market, the increasing efficiency of ICEV and the increasing in the share of electric/hydrogen vehicles. Among the RES, the most significant increase is due to the ambient heat, followed by solar energy, while hydro and biomass remain stable; electric import benefit from a growing share of RES in the national mix. The 2016 35% RES share (of supply, the national value is 18%) rises by 2030 to 41/49% in LC/LC+. At 2050 the PAT is approaching energy independence based on RES, in LC it is reached the 72%, in LC+ the 86%.

Energy efficiency and the increase in RES contribute to the reduction of CO2 emissions (Fig. 11 and Supplementary Materials C). The LC scenarios allow the achievement of the EU Energy and Climate Objectives, -40% at 2030 and -80% at 2050 (compared to 1990), while the LC+ scenarios, following a “tech rapid” trajectory, lead to -50% at 2030 and -90% at 2050.

3.9. PEAP scenarios: economic analysis

Economic values are analyzed in detail by the EnergyPLAN software. Results for the PEAP scenarios are shown in Fig. 12 and in Supplementary Materials C.

A first key message is that the REF, LC and LC+ trajectories have

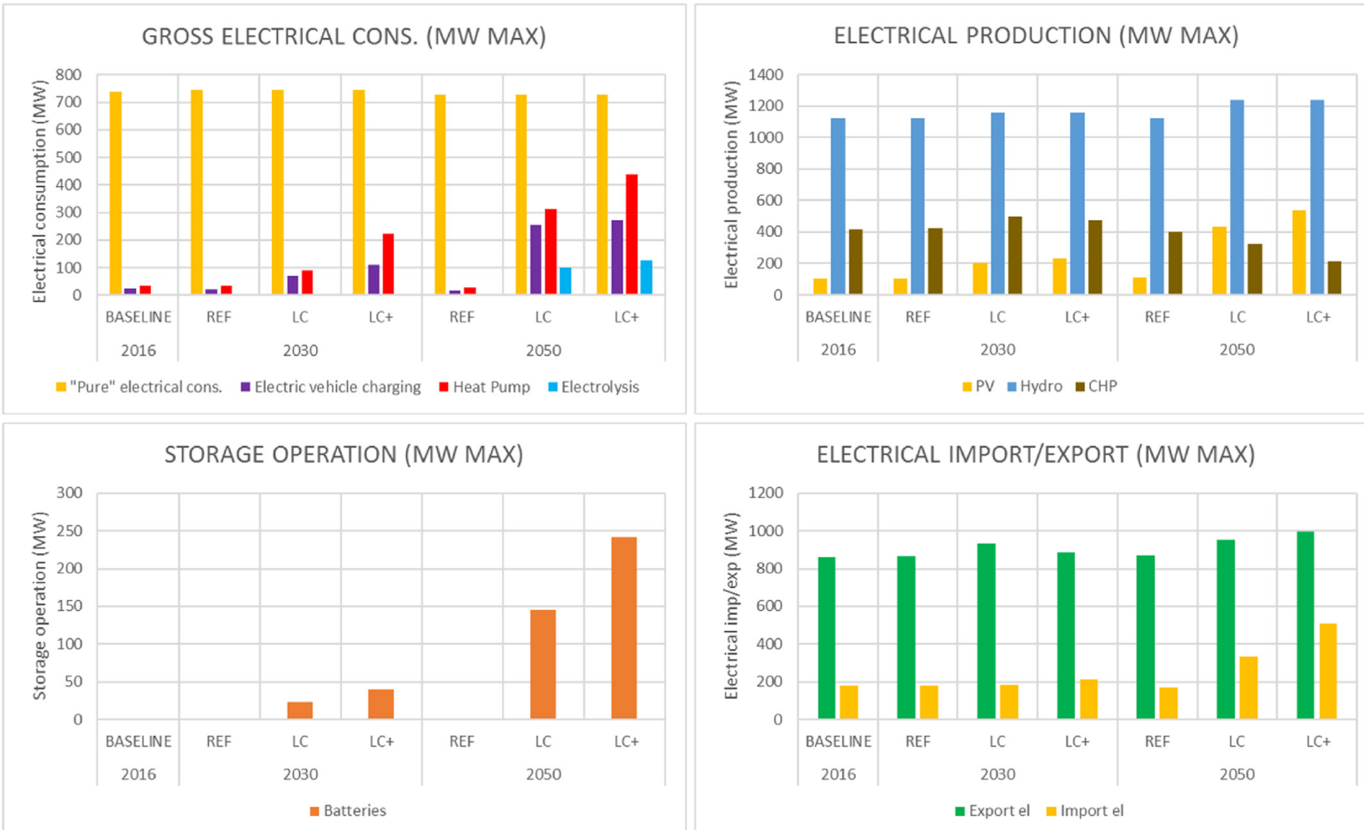

Fig. 10. PEAP scenarios - electricity sector - focus maximum hourly powers on the electricity grid (graphic display).

similar total annual cost, close to the Baseline 2016. Indeed, by 2030 the increase in total annual cost is limited to +4% in REF and LC, to +7% in LC+. At 2050 the deviation from the Baseline 2016 slightly increases up to +5% in REF, +11% in LC and +14% in LC+.

Despite these slight increases in total annual cost, splitting the cost items (energy carriers cost, operating cost and investment cost) a second key message emerges: in the LC and LC+ scenarios, investments in building efficiency and renewable technologies increase, while the cost of importing energy carriers (oil and gas) decreases: the impact on the PAT economy is highly positive.

Finally, a third key message comes from the comparison of the REF, LC and LC+ investment cost paths. An average annual differential between the REF and the LC/LC+ scenarios is estimated to be 97/174 M€ in 2016–2030, 425/574 M€ in 2030–2050. This means that the energy transition requires public incentives and private investments gradually increasing as the decarbonisation objectives increase. However, these incentives/investments are offset by lower costs for imported energy carriers and benefits for the local economy and workforce.

The benefits for the PAT economy are well illustrated in Fig. 13: while the REF scenario maintains a strong dependence on the foreign economy through a high share of the total annual cost dedicated to the import of energy carriers, from 28% in Baseline 2016 to 31% in 2030 and 30% in 2050, the LC/LC+ scenarios see this dependence drop significantly to 22/18% by 2030 and to 6/4% by 2050. By 2050 the PAT energy system is almost free from foreign energy carriers with almost all the costs that remain in the PAT territory by expense on local energy carriers, operating cost and investment cost. All this leads to benefits for the local economy and workforce.

4. Conclusions

This paper shows how a regional decarbonisation plan can be realized adopting an integrated view of the overall energy system and a dynamic approach in the balance between productions and consumptions. Moreover, it is proposed to combine the tool EnergyPLAN, to develop integrated and dynamic scenarios, with a MOEA, to identify solutions optimized both in terms of CO2 emission and total annual cost. Indeed, energy scenario design can be formulated as a multi-objective optimization problem.

Therefore, the methodological novelty of this work is the analysis of future energy scenarios with a framework that considers hourly profiles, intelligent integration of different energy sectors and storage options, integration of multi-objective optimization and analysis of transition paths. These aspects are innovative considering that the standard energy scenario analysis is based on annual balances, does not consider intelligent sector coupling and lacks proper optimization. The proposed scenarios not only meet future objectives in terms of CO2 emissions, energy efficiency and use of RES, but also identify how it will be possible to achieve them with minimal cost, this has important benefits for the local economy and workforce.

In the PAT case study the integrated vision results strategic in applying sector coupling solutions among the large production from local electric RES (hydroelectric in particular), the thermal demand (through heat pumps) and the transport demand (through electric mobility). Moreover, also the dynamic analysis results strategic to accurately evaluate the matching between consumption profiles and production profiles, a challenge in the growth of variable and non-programmable RES (such as hydro and solar).

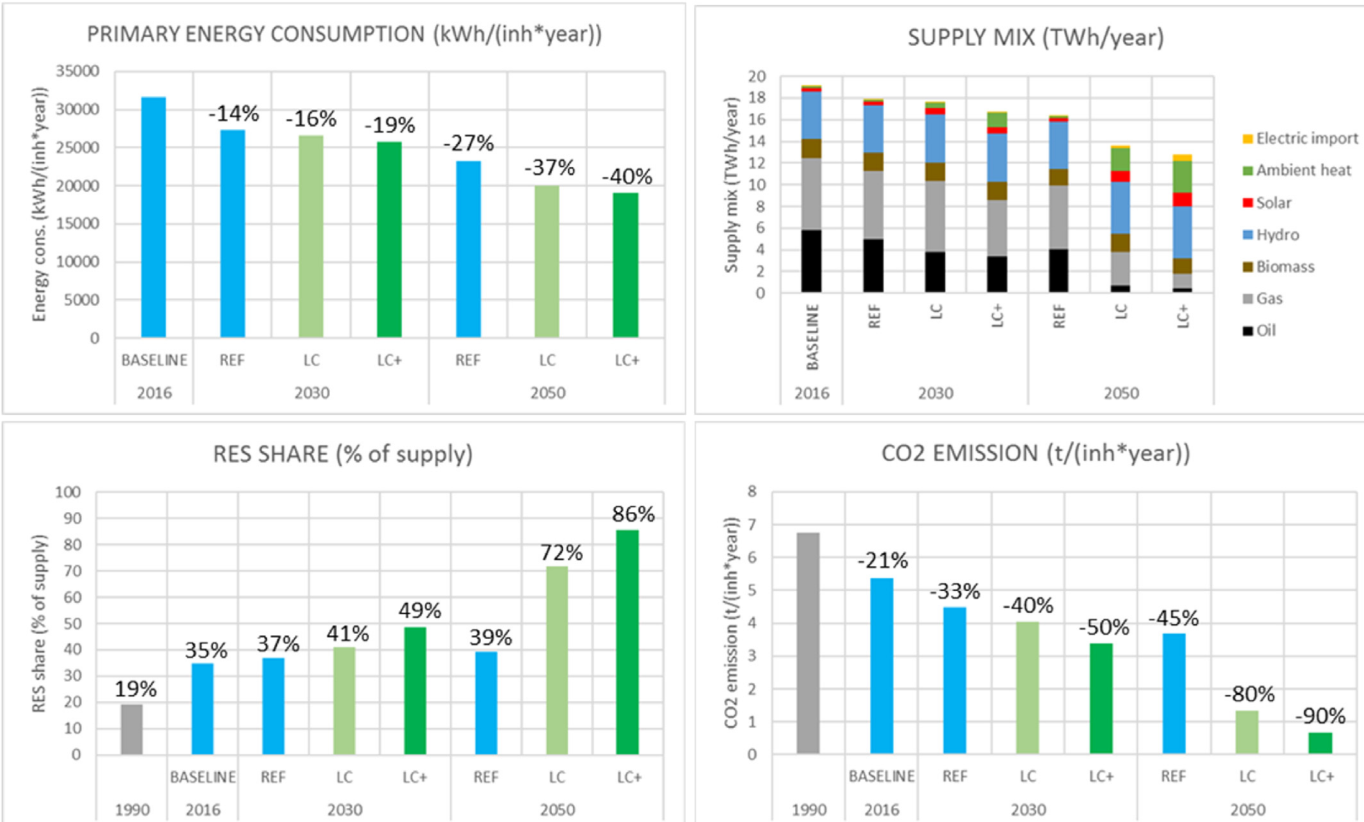

Fig. 11. PEAP scenarios - analysis of energy consumption, RES and CO2 emissions (graphic display).

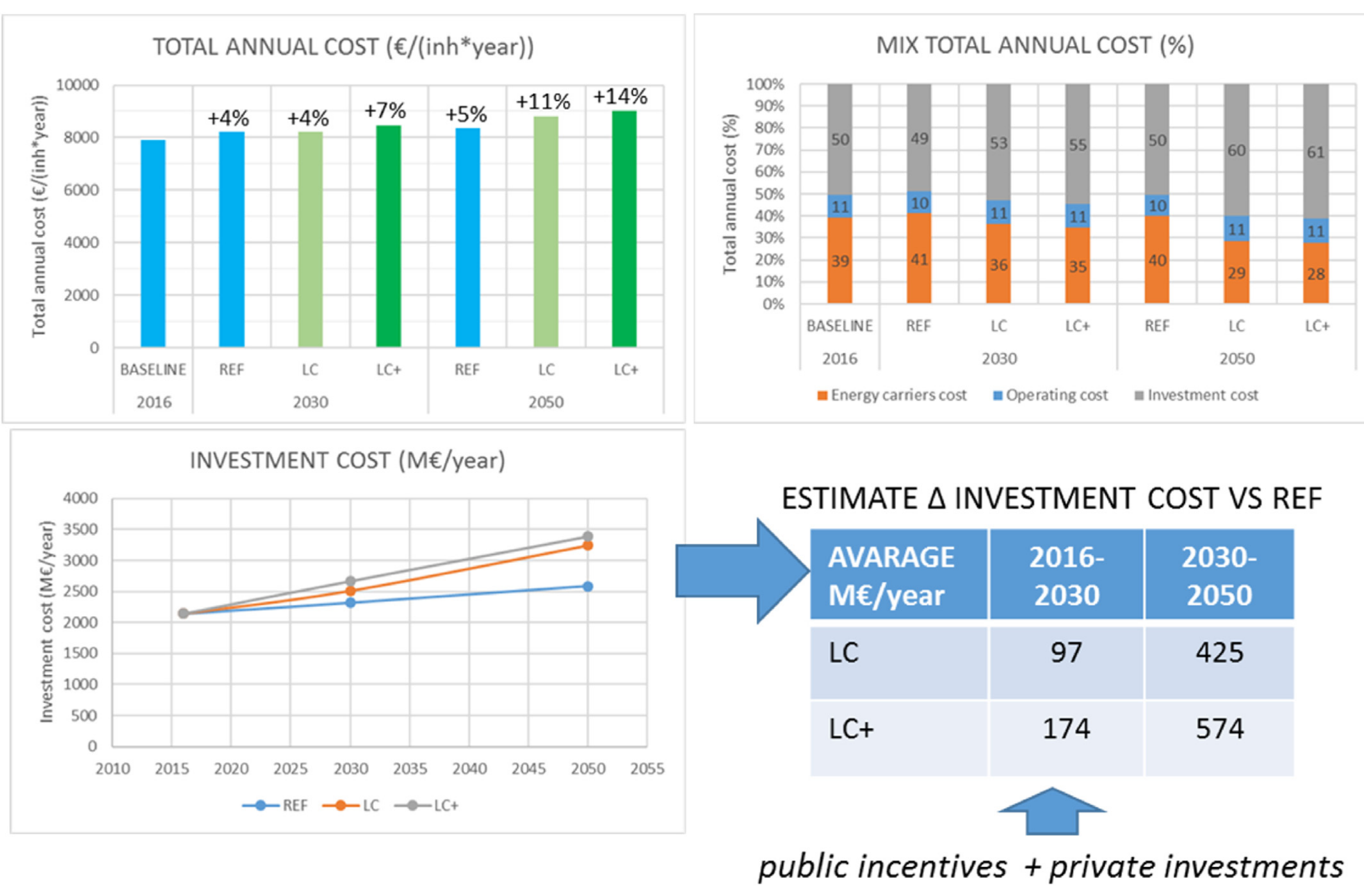

Fig. 12. PEAP scenarios - economic analysis (graphic display).

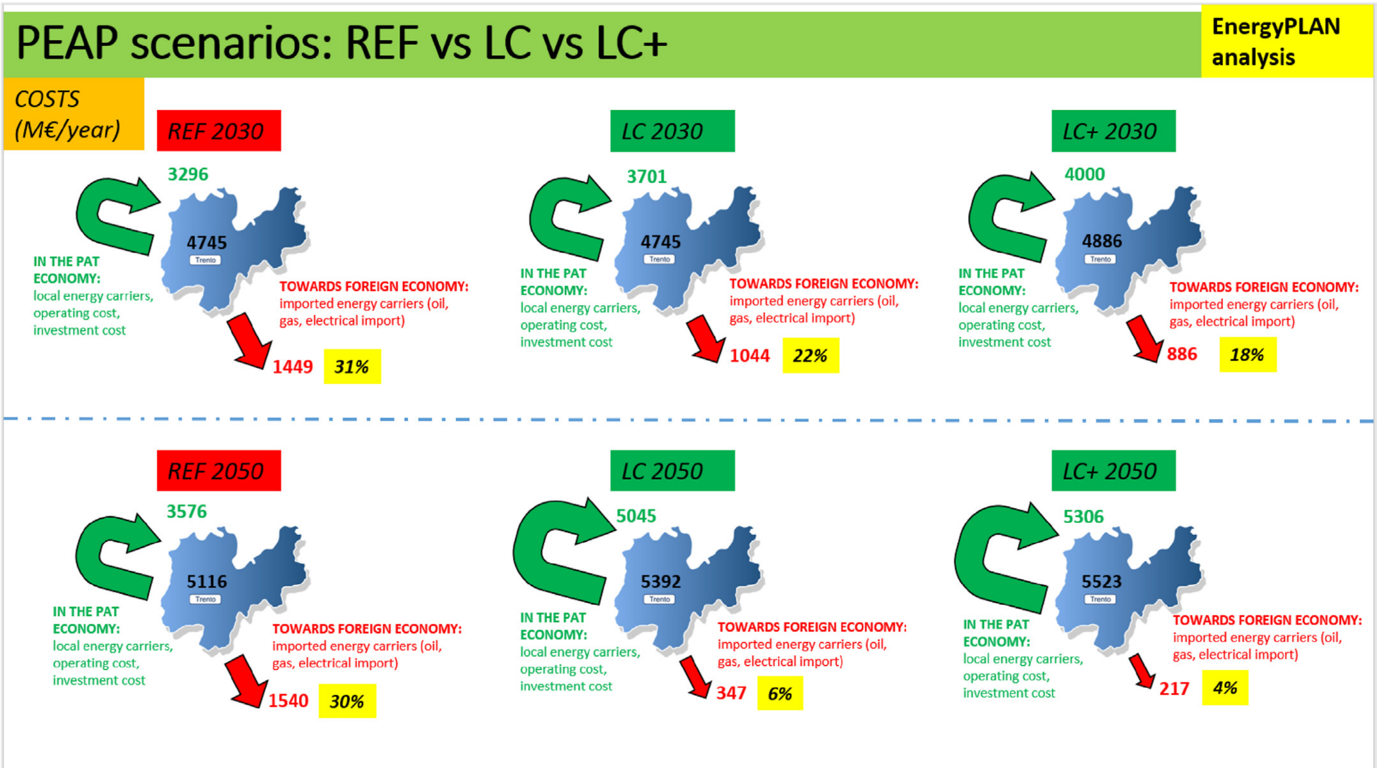

Fig. 13. PEAP scenarios - benefits for the PAT economy.

A detailed techno-environmental analysis has defined how the improvement of energy efficiency, the increase in RES integration and the "sector coupling" can contribute to significant reduction of CO2 emissions. The LC scenarios allow the achievement of the EU Energy and Climate Objectives, -40% at 2030 and -80% at 2050 (compared to 1990), while the LC+ scenarios, following a "tech rapid" trajectory, lead to -50% at 2030 and -90% at 2050. On the other hand, the techno-economic analysis has defined that only slight increases in total annual cost can occur, up to 14% in LC+ 2050 compared to the Baseline 2016. Moreover, costs breakdown highlights a significant fact: the PAT energy system can be almost free from foreign energy carriers (oil, gas) with almost all the costs that remain in the PAT territory by expense on local energy carriers, operating cost and investment cost. All this leads to benefits for the local economy and workforce.

In comparison with the other papers that adopt the EnergyPLAN + MOEA methodology at regional scale, identified in the Introduction (see Table 1), the PAT case study: (I) confirms the electrification of thermal and transport sectors as an optimal choice in minimizing both CO2 emission and total annual cost, enhancing local renewables (e.g. hydro, solar), (II) confirms the possibility of achieving a deep decarbonisation by 2050, in line with the EU objectives of the "2050 long-term strategy" (at least -80% CO2 emission compared to 1990), while keeping total annual cost very close to the current one.

Overall, these results enable local policy makers to identify attractive tailor-made policies that could direct a deep decarbonisation, in a moderate (LC) or rapid (LC+) transition, towards cost-effective paths.

CRediT authorship contribution statement

Diego Viesi: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Writing - original draft, Visualization. **Luigi Crema:** Conceptualization, Methodology, Validation, Resources, Writing - review & editing. **Md Shahriar Mahbub:** Conceptualization, Methodology, Software, Validation, Investigation, Writing - review & editing. **Sara Verones:** Validation, Resources, Writing - review & editing, Funding acquisition. **Roberto Brunelli:** Validation, Resources, Writing - review & editing, Funding acquisition. **Paolo Baggio:** Validation, Resources, Writing - review & editing. **Maurizio Fauri:** Validation, Resources, Writing - review & editing. **Alessandro Prada:** Validation, Resources, Writing - review & editing. **Andrea Bello:** Validation, Resources, Writing - review & editing. **Benedetta Nodari:** Validation, Resources, Writing - review & editing. **Silvia Silvestri:** Validation, Resources, Writing - review & editing. **Luca Tomasi:** Validation, Resources, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2020.118378.

Appendix A

Decision variables and boundaries for the EnergyPLAN + MOEA analysis

The EnergyPLAN + MOEA analysis for the PAT case study considers 14 variable value technologies, 4 linked value technologies and 6 fixed value technologies.

The variable value technologies consider values provided by MOEA, with the lower limit set to 0, guaranteeing maximum flexibility to the MOEA, while the upper limit takes into account the following constraints. ELECTRICITY PRODUCTION: (1) limited availability of additional water resources for hydroelectric production [53]; (2) for the PV twice the production expected from national and local trends [53]. COGENARATION + THERMAL PRODUCTION: (1) FEM scenarios for the increase in biogas CHP production; (2) limited social attractiveness to increase 2016 use of biomass boilers (wood procurement and policy issues related to the particulate matter emissions of wood combustion); (3) for technologies that do not use biomass the total individual thermal demand is considered. TRANSPORT SECTOR: (1) total transport demand in km. STORAGE: (1) for the batteries an amplified ratio with the maximum installable PV[9].

The linked value technologies consider values calculated by EnergyPLAN in each simulation. These are: national electricity grid (import, export), electrolyzer, thermal storage, hydrogen storage.

The fixed value technologies consider values defined by the PEAP working group analysing the Baseline 2016 and future trends. These are: DH technologies (CHP, boiler) and energy efficient building envelopes.

EnergyPLAN+MOEA: decision variables & boundaries

Technology	2030					2050				
	MOEA LB LC&LC+	LC	LC+	MOEA HB LC	MOEA HB LC+	MOEA LB LC&LC+	LC	LC+	MOEA HB LC	MOEA HB LC+
ELECTRICITY PRODUCTION										
Hydroelectric (TWh)	0			4.673	4.673	0			4.998	4.998
PV (TWh)	0			0.700	0.800	0			1.480	1.860
National electricity grid (TWh)	Calculated by EnergyPLAN, no grid constraints					Calculated by EnergyPLAN, no grid constraints				
COGENERATION (thermal production)										
CHP biogas (TWh)	0			0.038	0.042	0			0.044	0.052
CHP/Indiv gas (TWh)	0			6.888	6.738	0			6.408	6.021
CHP/DH biomass (TWh)		0.067	0.066				0.063	0.059		
CHP/DH gas (TWh)		0.101	0.099				0.094	0.088		
THERMAL PRODUCTION										
Solar thermal (TWh)	0			6.888	6.738	0			6.408	6.021
Heat Pump (TWh)	0			6.888	6.738	0			6.408	6.021
Boiler/Indiv oil (TWh)	0			6.888	6.738	0			6.408	6.021
Boiler/Indiv LPG (TWh)	0			6.888	6.738	0			6.408	6.021
Boiler/Indiv gas (TWh)	0			6.888	6.738	0			6.408	6.021
Boiler/Indiv biomass (TWh)	0			1.384	1.354	0			1.288	1.210
Boiler/DH biomass (TWh)		0.023	0.022				0.021	0.020		
Boiler/DH gas (TWh)		0.038	0.038				0.036	0.034		
Boiler/DH oil (TWh)		0.004	0.004				0.003	0.003		
HYDROGEN PRODUCTION										
Electrolyzer (MW)	Calculated by EnergyPLAN as minimum capacity needed					Calculated by EnergyPLAN as minimum capacity needed				
TRANSPORT SECTOR										
Transport el (Mkm)	0			10071	10071	0			10700	10700
Transport H2 (Mkm)	0			10071	10071	0			10700	10700
Transport petrol (Mkm)	0			10071	10071	0			10700	10700
STORAGE (capacity)										
Thermal storage (GWh)	Considered a capacity of 1 day of average heat demand					Considered a capacity of 1 day of average heat demand				
Battery storage (GWh)	0			2.635	3.022	0			5.522	6.905
Hydrogen storage (GWh)	Considered a capacity of 1 day of average H2 demand					Considered a capacity of 1 day of average H2 demand				
BUILDINGS										
Energy eff. build. env. (TWh)		1.147	1.309				1.364	1.705		

A VERY COMPLEX OPTIMIZATION PROBLEM...

- **14 variable value technologies** (values provided by MOEA, from 0 to max allowed by resource availability, social attractiveness, amplified trends, sector demand)
- **4 linked value technologies** (values calculated by EnergyPLAN: national electricity grid, electrolyzer, thermal storage, hydrogen storage)
- **6 fixed value technologies** (values defined by the PEAP working group considering Baseline 2016 + trends)

Fig. 14. EnergyPLAN + MOEA: decision variables & boundaries.

[9] 100% PV power involved in the coupling, every 3 kW of PV 12 kWh of batteries, every 6 kWh of battery storage 3 kW of battery peak power.

Appendix B

PAT scenarios: technological comparison 2030 and 2050. In red dashed line the reduction of CO2 emissions compared to 1990.

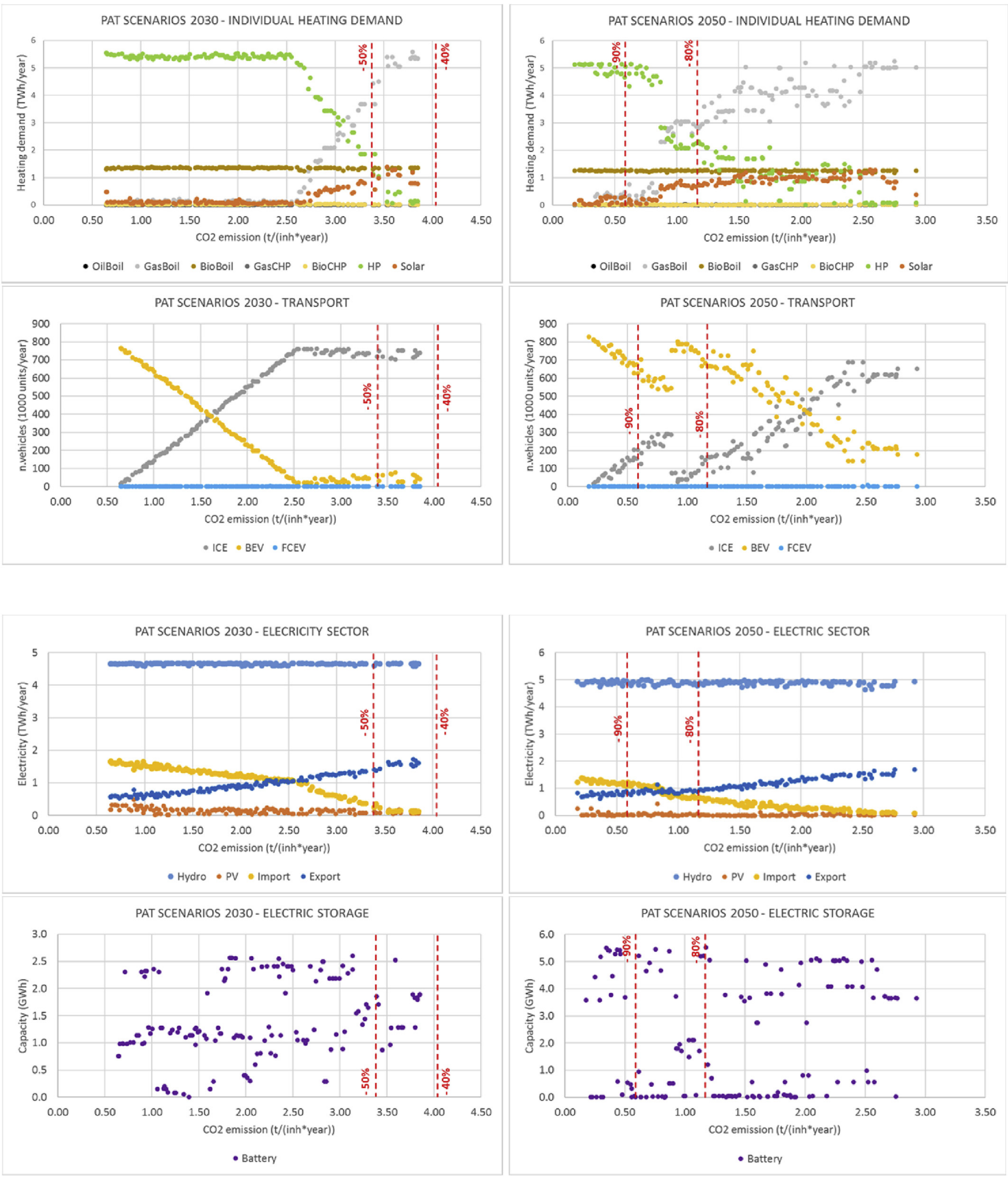

Fig. 15. PAT scenarios: technological comparison 2030 and 2050. In red dashed line the reduction of CO2 emissions compared to 1990. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Appendix C

PEAP results: hourly profiles in the electricity grid

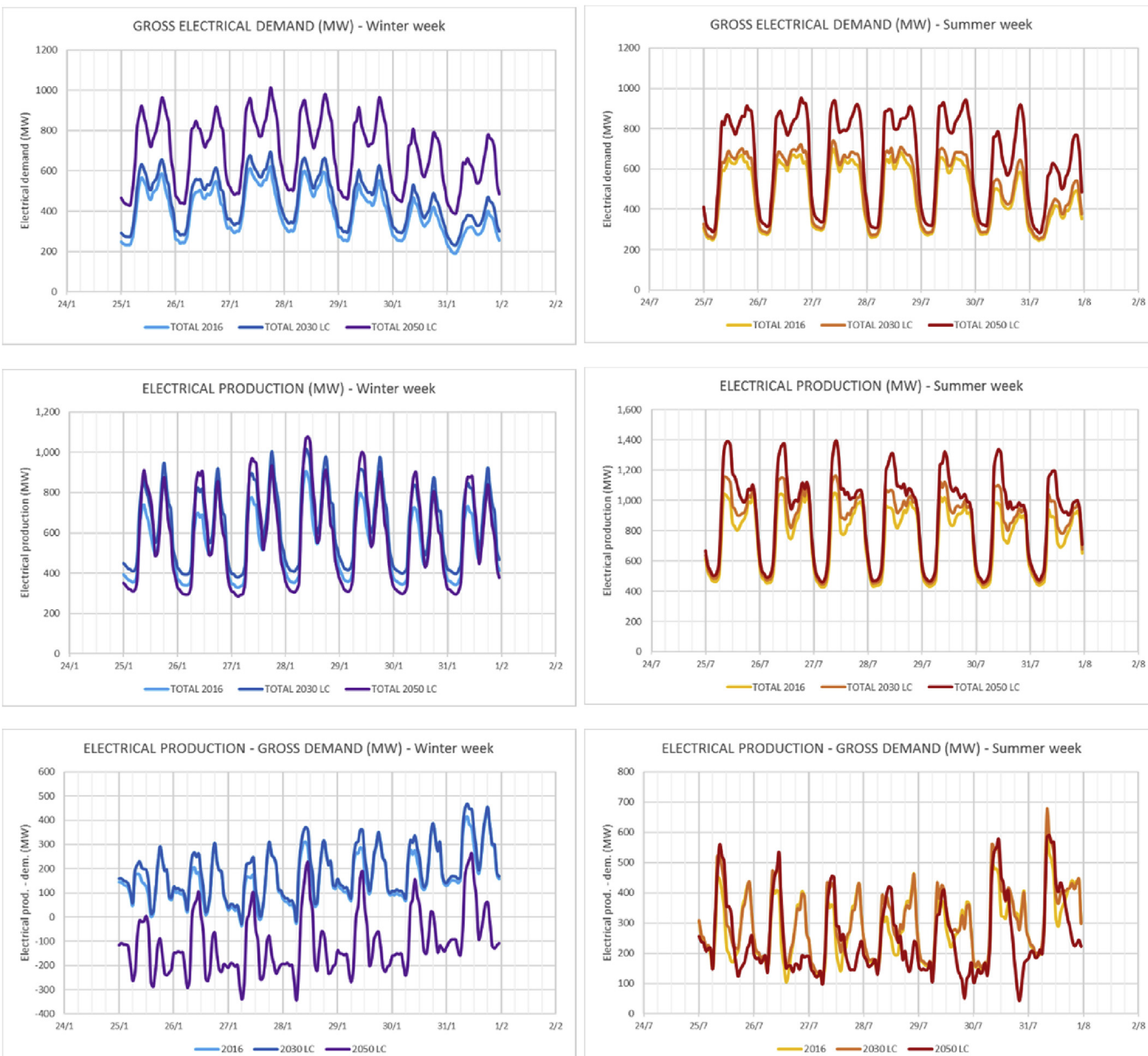

Fig. 16. PEAP scenarios - hourly profiles in the electricity grid.

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